



Carbon dioxide and water fluxes from switchgrass managed for bioenergy production

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ABSTRACT

Switchgrass (*Panicum virgatum* L.) is an important bioenergy crop with the potential to provide a reliable supply of renewable energy while also sequestering C in the soil. The purpose of this study was to quantify CO₂ fluxes during the establishment and early production years of a young switchgrass stand in the northeastern USA. Switchgrass was sown in June 2004 and daily CO₂ fluxes were measured for four years. Gross primary productivity (GPP) varied little among years, but ecosystem respiration (Re) decreased over time. The switchgrass generally began to take up CO₂ in mid-May and continued until early-October, and was a net sink during a 98-day period from late-May through early-September. The rest of the year experienced a net loss of CO₂ to the atmosphere. Harvested biomass increased each year and was not related to GPP. The switchgrass field was a net CO₂ sink for the first three years, but became a source the final year due to increased removal of C as harvested biomass. This study suggests that in addition to their primary function as a source of renewable energy, switchgrass bioenergy crops in the northeastern USA can sequester CO₂ for at least the first few years following establishment.

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1. Introduction

Switchgrass is a fast-growing resource-efficient species that has potential as a bioenergy crop for the production of both ethanol and electric power (McLaughlin et al., 2002). A life cycle assessment of net greenhouse gas fluxes for various bioenergy cropping systems found that hybrid poplar and switchgrass provided larger greenhouse gas sinks than corn, soybean, alfalfa, or reed canarygrass, and that compared with the life cycle of gasoline or diesel, switchgrass reduced greenhouse gas emissions by 144% (Adler et al., 2007) due primarily to displaced fossil fuel use and to soil C sequestration. The perennial growth habit and high root productivity of switchgrass, especially in deep soil layers, make it a potentially ideal crop for sequestering soil C (Frank et al., 2004; Liebig et al., 2005).

However, information is limited on the carbon sequestration potential of switchgrass, especially in the eastern USA. Estimates range from highs of 3700 g CO₂ m⁻² yr⁻¹ during the first three years after establishment in the northern Great Plains (Frank et al., 2004) to virtually no sequestration in two- to five-year old stands in the southeastern USA (Garten and Wullschlegel, 2000; Ma et al., 2000). Typical sequestration rates range from about 110 to 1500 g CO₂ m⁻² yr⁻¹ (Al-Kaisi et al., 2005; Lee et al., 2007b; Liebig et al., 2008; Omonode and Vyn, 2006). Increased N fertility has

been shown to increase C sequestration in a mature switchgrass stand (Lee et al., 2007b) but had no effect on soil organic C during the first two to three years after stand establishment (Ma et al., 2000). No information could be found on soil C sequestration under switchgrass for the northeastern USA. However, a simulation of greenhouse gas fluxes for bioenergy crops grown in central Pennsylvania suggested that switchgrass could sequester 157 g CO₂ m⁻² yr⁻¹ (Adler et al., 2007). The purpose of this study was to help fill the gap in regional estimates of switchgrass C sequestration potential by using micrometeorological techniques to quantify CO₂ flux and evapotranspiration during the establishment and early production years of a young switchgrass stand in the northeastern USA.

2. Materials and methods

2.1. Site description, preparation and management

'Cave-in-Rock' switchgrass (*Panicum virgatum* L.) was established on a private farm near Ligonier, Westmoreland Co., Pennsylvania (40°19'11" N 79°6'40" W, elevation 460 m) in June 2004 on an approximately rectangular 9.34-ha site that was about 500 m long in the SW to NE direction and about 200 m wide from NW to SE. The site had been in perennial grasses for at least five years prior to beginning the experiment. The soil was a Gilpin channery silt loam (Fine-loamy, mixed, active, mesic Typic Hapludults). Soil organic C in the 0–5 and 5–10 cm depths was 25.8 ± 1.2 and

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$18.8 \pm 1.2 \text{ g kg}^{-1}$, respectively. The C:N ratio in the 0–10 cm depth was 9.5. Soil nutrient analysis suggested that both P and K levels were well within the optimum range for warm-season grass so no additional P or K was added during the study.

Preparation for switchgrass establishment began in June 2001 when the pasture was spot sprayed for woody weeds then rotary mowed. The pasture was again mowed to a height of 5–7 cm in April 2002, sprayed with Roundup ultra at a rate of 3.5 L ha^{-1} and planted with an oat (*Avena sativa* L.) cover crop. The oats were sprayed in September 2002 with a combination of Roundup ultra at 3.5 L ha^{-1} and 2,4-D at 0.6 L ha^{-1} . 'Cave-in-Rock' switchgrass was originally planted in spring 2003, but strong weed competition resulted in a poor stand. As a consequence, the site was moldboard plowed, disked, harrowed, cultipacked, and planted to winter wheat (*Triticum aestivum* L.) in October 2003. The wheat was sprayed with Roundup ultra at 4.5 L ha^{-1} on 20 May 2004 and 'Cave-in-Rock' switchgrass planted on 1 June 2004. No-till establishment practices were employed for all crops except for the tillage operations prior to planting winter wheat in 2003.

A spring harvest management schedule was employed wherein the crop was allowed to over-winter in the field then was harvested in the spring shortly before the next season's growth began (Adler et al., 2006). Because of limited growth the first year, no harvest was taken in spring 2005. Fertilizer was applied at 56 kg N ha^{-1} as urea on 9 June 2005 and as ammonium sulfate on 14 June 2006, and 5 July 2007. Biomass was mechanically harvested on 20 April 2006, 3 May 2007, and 22 April 2008. The switchgrass was baled and weighed then subsamples from each bale were oven dried at 55°C to determine moisture content. All yields are expressed on a dry weight basis. Because the crop was allowed to overwinter in the field, extensive lodging occurred and a substantial portion of the crop was not picked up by the harvester. To quantify this residual biomass, 20 1.0-m^2 randomly located samples were manually cut to a stubble height of 12.5 cm and all leaves and stems produced during the previous summer were collected, dried at 55°C and weighed.

2.2. Flux measurements

Following seedling emergence, an eddy covariance system was placed in the field and daily CO_2 and water vapor flux measurements began on 1 October 2004. Flux measurements continued until 30 September 2008. The eddy covariance tower was located on a small knoll which sloped away from the tower in all directions at a 3–8% grade. Field-scale CO_2 and H_2O fluxes were quantified using a Campbell Scientific¹ eddy covariance system featuring a LI-7500 open path $\text{CO}_2/\text{H}_2\text{O}$ analyzer and CSAT3 3-D sonic anemometer (Campbell Scientific Inc., Logan, UT). This system uses micrometeorological techniques to monitor biosphere–atmosphere exchanges of CO_2 and H_2O by correlating fluctuations in vertical wind velocity with changes in flux density (Dugas et al., 1991). Data were collected continuously at 10 Hz and averaged over 20-min time intervals. The open-path $\text{CO}_2/\text{H}_2\text{O}$ analyzer and CSAT3 3D sonic anemometer were placed at a constant height of 2.1 m above the soil surface at a location in the field that provided 150–380 m fetch in the direction of the prevailing winds. Fetch in other directions ranged from 90 to 140 m. About 70% of the study location was surrounded by hardwood forest with the remaining border consisting of an abandoned agricultural field and a large cool-season grass lawn. Coordinate rotation, frequency response corrections (Moore, 1986), corrections for density effects due to heat and water vapor

transfer (Webb et al., 1980), and corrections for internal and external heating of the LI-7500 (Burba et al., 2008) were applied to the raw CO_2 flux data. The meteorological sign convention is used throughout the manuscript, wherein positive fluxes indicate loss to the atmosphere and negative fluxes indicate uptake into plants and soil.

Raw flux data provide an estimate of net ecosystem exchange (NEE) which represents the difference between photosynthetic uptake or gross primary productivity (GPP) and ecosystem respiration (Re). The NEE data were mathematically partitioned into GPP and Re components. Nighttime NEE was considered to be equivalent to nighttime Re. To calculate daytime Re, an equation was developed relating nighttime Re to soil temperature (T_{soil}) using a single three parameter exponential growth equation for each year. The equations were then used to calculate daytime Re based on daytime T_{soil} . Nighttime and daytime Re were then summed to obtain total Re. Gross primary productivity was estimated by subtracting daytime Re from daytime NEE.

Frequent gaps in eddy covariance data resulted whenever rain-water or dew coated the LI-7500 and CSAT3 sensors. Flux data also became unreliable when winds were calm and friction velocity (u^*) decreased below about 0.12 m s^{-1} . Low u^* generally occurred at night and during early morning hours. Approximately 50% of the data typically needed to be discarded because of the frequent rainfall (about 1000 mm yr^{-1}) and low wind velocity characteristic of this study site. Gap filling procedures were used to replace spurious and missing values. In a few cases, when only one or two consecutive 20-min values were missing, gaps were filled by interpolating between valid data points. Most nighttime missing CO_2 data, however, were estimated by regressing nighttime NEE against T_{soil} (Xu and Baldocchi, 2004). During the growing season, daytime missing CO_2 values were estimated from light response curves derived from daytime NEE regressed against photosynthetically active radiation (PAR) using three parameter exponential decay equations. Because the relationship between daytime NEE and PAR varies with temperature, soil water status and leaf area, new regressions were calculated at approximately 5–10 d intervals whenever visual inspection of the data suggested that substantial changes in equation parameters had occurred. Evapotranspiration (ET) was calculated by dividing latent heat flux by the latent heat of vaporization. Good correlations existed between ET and net radiation (R_{net}) over relatively short intervals of one to two months. Therefore, a three parameter exponential growth function relating ET to R_{net} was calculated for each 30-d period to fill gaps in water vapor flux. Water use efficiency (WUE) was calculated for each 20-min measurement period by dividing GPP by ET.

Ancillary data were collected at 20 min intervals at each site and included, air temperature and relative humidity (HMP45C temperature and RH probe, Vaisala, Woburn, MA), net solar radiation (Q7.1 net radiometer, REBS, Seattle, WA), photosynthetically active radiation (190SZ quantum sensor, Li-Cor, Lincoln, NE), soil temperature at a depth of 3 cm (Campbell Scientific model 107 soil temperature probe), volumetric soil moisture at 5 and 30 cm depths (Campbell Scientific CS616 water content reflectometer), and rainfall (TE525 tipping bucket rain gauge, Texas Electronics, Dallas, TX).

3. Results

Average annual precipitation and air temperature (T_{air}) for nearby communities are 1230 mm and 10.1°C , respectively. During the four years of this study, T_{air} was similar among years and slightly below average, ranging from 9.7 to 10.0°C (Table 1). There was also little difference in the maximum and minimum T_{air} experienced each year, with the minimum ranging from -18 to -21°C and the maximum from 31 to 33°C . Average annual soil temperature (T_{soil})

¹ Mention of a specific brand name is for identification purposes only and does not constitute endorsement by the USDA-ARS at the exclusion of other appropriate sources.

Table 1

Total annual precipitation, mean annual soil and air temperature, and maximum and minimum soil and air temperature for 12-month periods beginning 1 October each year. Soil temperature was measured at a depth of 5 cm.

Year	Precipitation (mm)	Soil temperature		Air temperature	
		Mean (°C)	Range (°C)	Mean (°C)	Range (°C)
2004–2005	868	11.4	–1 to 28	10.0	–19 to 33
2005–2006	995	10.7	0 to 25	9.7	–18 to 32
2006–2007	1071	10.7	0 to 22	9.9	–21 to 33
2007–2008	1059	10.1	0 to 22	9.8	–18 to 31

decreased each year from a maximum of 11.4 °C in 2004–2005 to 10.1 °C in 2007–2008. In 2004–2005, T_{soil} was 1.4 °C greater than T_{air} . This difference decreased each year to 1.0 °C in 2005–2006, 0.8 °C in 2006–2007, and 0.3 °C in 2007–2008.

Annual precipitation for all years was below the long-term average, ranging from 868 to 1071 mm yr^{–1} (Table 1). The warmest year, 2004–2005, was also the driest. Growing season soil moisture near the surface (5 cm depth) was highly variable with multiple drying and wetting periods each year (Fig. 1). In 2005, drought persisted through most of the spring and early summer so that volumetric soil moisture at 30 cm steadily declined from April until the beginning of August, reaching the lowest value recorded during the study at 12.5% on 8 August. Although 2006 was the second driest year, timely rainfall during the summer kept soil moisture at 30 cm above 20% for most of the summer. The last two years of the study had the greatest rainfall, but both experienced periods of drought. In 2007, persistent drying occurred during May and June, whereas, in 2008 the greatest drying occurred from mid-July through mid-September.

The amount of harvested biomass increased each year as the stand matured. There was not sufficient biomass available in 2005 to justify a harvest and all biomass produced in 2004 was left standing in the field. Harvested biomass increased from 94 g dry

matter m^{–2} for the spring 2006 harvest to 386 g m^{–2} in 2007 and 597 g m^{–2} in 2008. The amount of residual biomass in 2006 was 152 g m^{–2}, and was greater than the harvested biomass. Residual biomass was 302 and 216 g m^{–2} in 2007 and 2008, respectively. Thus, total biomass production was 246 g m^{–2} during the 2005 growing season (harvest in 2006), 688 g m^{–2} in 2006 (harvested in 2007), and 813 g m^{–2} in 2007 (harvested in 2008). No attempt was made to measure the amount of biomass produced in 2004. However, given the increase in biomass production in subsequent years, it is likely that production in 2004 and, thus, the amount left standing in the field was less than 200 g m^{–2} and possibly less than 100 g m^{–2}.

Annual CO₂ fluxes and soil carbon sequestration were calculated for each 12-month period from 1 October to 30 September. Annual gross primary productivity (GPP) was remarkably stable across years, ranging from –3355 to –3451 g CO₂ m^{–2} yr^{–1} (Table 2). Ecosystem respiration decreased substantially during the first three years of the study, from 3339 g CO₂ m^{–2} in 2004–2005 to 2487 g CO₂ m^{–2} in 2006–2007. Thus, the increase in NEE in the second and third years was due to decreasing Re rather than to increasing GPP. Both GPP and Re were low from November through April then increased as temperature warmed and the grass began to grow. Ecosystem respiration began to increase somewhat earlier in the

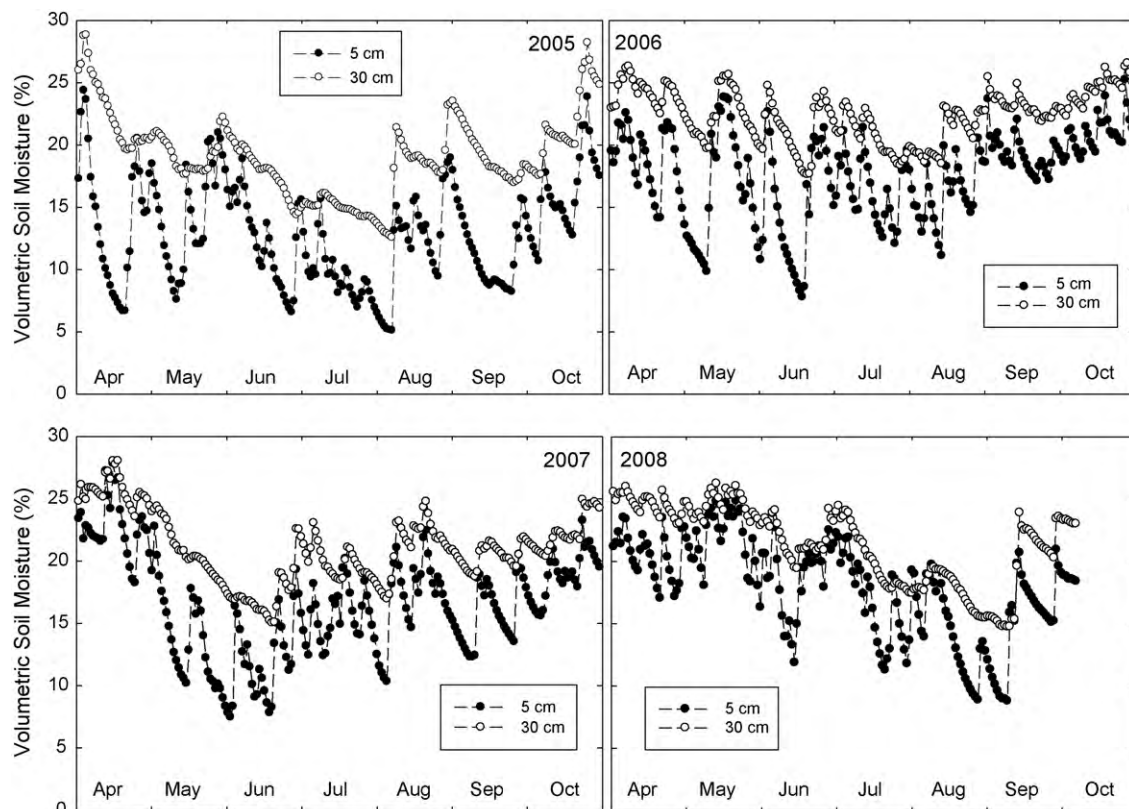


Fig. 1. Mean daily soil moisture at 5 and 30 cm depths from 1 April through 31 October each year.

Table 2

Annual gross primary productivity (GPP), ecosystem respiration (Re), net ecosystem exchange (NEE), and net biome productivity (NBP) for a spring-harvested switchgrass bioenergy crop during four years following seedling establishment. The CO₂-equivalent (CO₂-e) of the harvested biomass was calculated using the assumption that biomass was 40% carbon. Net biome productivity equals the sum of GPP, Re, and harvested biomass. Negative values indicate uptake and positive values indicate loss from the ecosystem.

Year (October–September)	GPP (g CO ₂ m ⁻²)	Re (g CO ₂ m ⁻²)	NEE (g CO ₂ m ⁻²)	Harvest (g CO ₂ -e m ⁻²)	NBP (g CO ₂ -e m ⁻²)
2004–2005	–3451	3339	–112	0	–112
2005–2006	–3359	2927	–432	137	–295
2006–2007	–3397	2487	–910	566	–344
2007–2008	–3355	2661	–694	876	182

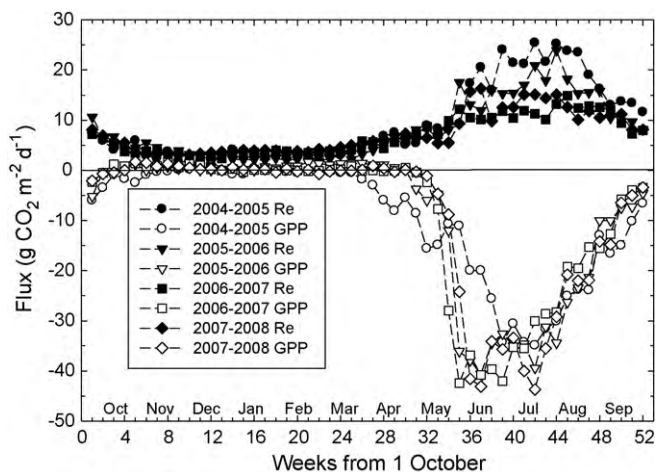


Fig. 2. Ecosystem respiration (Re) and gross primary productivity (GPP) over a 12-month period beginning 1 October each year. Fluxes are presented as daily means averaged over 7-d periods. Positive flux indicates CO₂ loss to the atmosphere from plant and soil respiration, whereas, negative flux indicates photosynthetic uptake by plants.

spring than did GPP (Fig. 2). The exception was in the spring of 2005 when GPP began to increase about 5–6 wk earlier than in later years. The greatest GPP was observed during June and July, whereas, peak Re extended into August. During most years, net CO₂ uptake (negative NEE) was restricted to the period from mid-May through early-September, whereas, the rest of the year experienced a net loss of CO₂ to the atmosphere (Fig. 3). Again the exception was 2005 when NEE first became negative about three weeks earlier than in subsequent years.

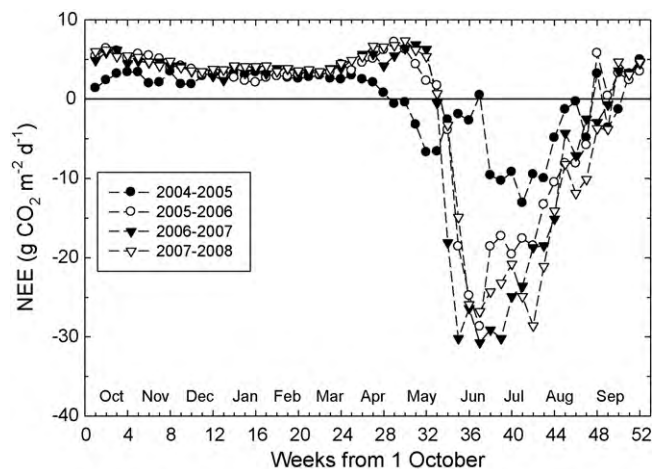


Fig. 3. Net ecosystem exchange (NEE) over a 12-month period beginning 1 October each year. Net ecosystem exchange equals the sum of ecosystem respiration and gross primary productivity. Positive flux represents a net loss of CO₂ to the atmosphere, whereas, a negative flux represents net uptake by the ecosystem. Fluxes are presented as daily means averaged over 7-d periods.

Net biome productivity (NBP) represents the sum of all CO₂ fluxes into and out of a field including photosynthesis, respiration, manure and other C inputs, and harvest removal. The NBP is a measure of the amount of CO₂ sequestered each year. At this study site there were no additions C inputs other than through photosynthesis. However, in addition to respiratory losses a portion of the fixed CO₂ was removed each spring when the switchgrass was harvested. Net biome productivity was negative the first three years of the study (Table 2), indicating that the field was a CO₂ sink. In 2007–2008, the harvested biomass exceeded NEE so that NBP was positive and the field was a net source of CO₂ to the atmosphere. Averaged across years, this field was a net sink with a mean NBP of –142 g CO₂ m⁻² yr⁻¹.

Annual evapotranspiration (ET) averaged 474 mm yr⁻¹, decreasing each year from a high of 515 mm yr⁻¹ in 2004–2005 to 446 mm yr⁻¹ in 2007–2008. During the winter months, ET averaged about 0.5 mm d⁻¹ (Fig. 4). Evapotranspiration began to increase each year at the same time as the increase in GPP. Maximum ET occurred from June through early-August and averaged about 3.0–3.75 mm d⁻¹. Combined across years, growing season (1 May to 30 September) GPP and ET were significantly correlated with each other ($r^2 = 0.87$, $P < 0.01$). Just as GPP remained constant across years, growing season ET also changed little, ranging from 331 to 358 mm for the May to September period. However, October to April ET decreased substantially each year, from 158 mm in 2004–2005 to 88 mm in 2007–2008. In 2005, water use efficiency (WUE) reached peak values in July then gradually declined during the rest of the growing season (Fig. 5). In contrast, peak WUE during the following three years occurred in early-June then remained high during the rest of June and July. As in 2005, WUE also gradually declined during August and September.

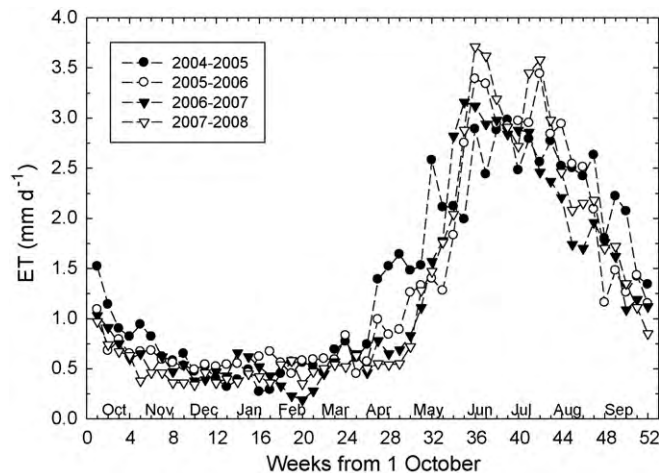


Fig. 4. Evapotranspiration (ET) over a 12-month period beginning 1 October each year. Fluxes are presented as daily means averaged over 7-d periods.

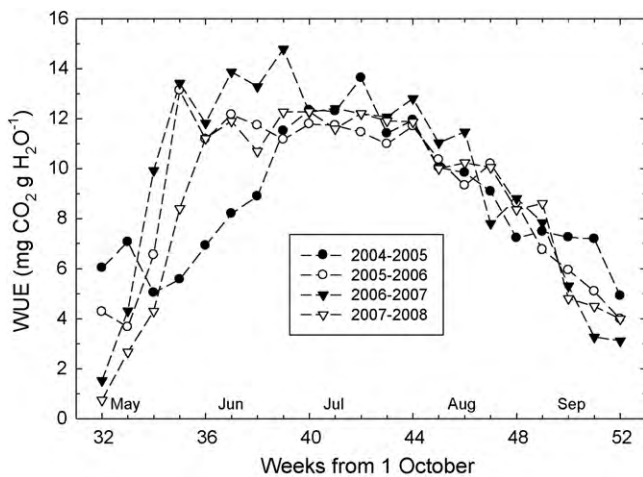


Fig. 5. Water use efficiency (WUE) over a 12-month period beginning 1 October each year. Data are presented as daily means averaged over 7-d periods.

4. Discussion

Averaged over four-years, this field sequestered $142 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$. The amount of CO_2 sequestered increased each year for the first three years as NEE increased more than the increase in harvested biomass (Table 2). However, a small decrease in GPP in 2007–2008 compared with the previous year (-1%), combined with a small increase in Re ($+7\%$) and a large increase in harvested biomass ($+55\%$) caused the field to experience a net loss of CO_2 in 2007–2008. The annual amount sequestered was considerably less than has been observed for switchgrass in the Midwest and Great Plains. Mature switchgrass stands sequestered $440 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ in a study in Iowa (Al-Kaisi et al., 2005) and $880 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ in South Dakota (Lee et al., 2007b). In North Dakota, a new switchgrass planting sequestered $3700 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ during the first three full years following sowing (Frank et al., 2004). However, in Alabama planting switchgrass did not change soil organic C during the first two to three years following establishment (Ma et al., 2000). Similarly, at four locations in Tennessee, Kentucky, and Virginia soil organic C did not differ significantly between switchgrass and fallow plots five years after establishment of the switchgrass even though the absolute amount of C under switchgrass was numerically greater (Garten and Wullschlegel, 2000). These results from the southeastern USA, combined with the current results from Pennsylvania, suggest that the carbon sequestration potential of switchgrass in the eastern USA may not be as great as in other regions of the country. However, additional data from many more sites will be needed before it can be determined if this is truly the case or not. The observed sequestration rate in this study was very close to simulated rates for Pennsylvania using the DAYCENT model (Adler et al., 2007), validating the usefulness of that model for predicting carbon sequestration potential of northeastern USA cropping systems.

A complete assessment of the C sequestration potential for this site requires knowledge of its' previous land use history as well as an assessment of potential C loss during preparation of the site for switchgrass establishment. The site existed as an essentially unmanaged grassland for at least five years before the study began but the previous history is unknown. Staley and Boyer (1997) found that surface soil organic C (SOC) on a Gilpin silt loam soil in West Virginia that had recently been brought under cultivation averaged about 30 g kg^{-1} . This was slightly greater than the 26 g kg^{-1} that we observed for the same soil type in the current study. This suggests that SOC at this site may have been somewhat depleted due to

previous land use history, although the difference between actual and attainable SOC (Sartori et al., 2006) was likely small.

Long-term tillage can reduce soil organic C by 50% or more compared with permanent pasture (David et al., 2009; Guo and Gifford, 2002), and even a one-time plowing of previously undisturbed grassland accelerated annual CO_2 emissions by 28–65% over a three year period (Grandy et al., 2006). Thus, even though the site was only plowed once in the fall of 2003, it is likely that some net loss of soil C occurred during preparation for switchgrass establishment. Decay and respiratory loss from the previous grassland could have also contributed to a net loss of C from the ecosystem during the two years between removal of the unmanaged grassland and successful switchgrass establishment.

Although the purpose of this study was to examine the C balance of a young switchgrass crop, N_2O emissions must also be considered when evaluating the greenhouse gas mitigation potential of cropping systems. No N_2O measurements were made in this study. However, Adler et al. (2007) estimated direct N_2O emissions from switchgrass growing in central Pennsylvania using both DAYCENT simulations and IPCC protocols. They found that N_2O emissions ranged from about $30\text{--}50 \text{ g CO}_2\text{-e m}^{-2} \text{ yr}^{-1}$ with IPCC estimates being lower than DAYCENT simulations. Including N_2O emissions in the calculation would reduce the mean annual greenhouse gas mitigation potential at this site from $-142 \text{ g CO}_2\text{-e m}^{-2} \text{ yr}^{-1}$ to about -90 to $-110 \text{ g CO}_2\text{-e m}^{-2} \text{ yr}^{-1}$.

The switchgrass in this study was managed using a spring harvest system, wherein the switchgrass is allowed to overwinter in the field then is harvested just before growth begins in the spring. This system results in lower moisture and mineral concentrations than under fall harvests (Adler et al., 2006). Lower water and mineral concentrations can improve safety in storage, reduce the cost of transportation, improve combustion efficiency, and reduce corrosion, slagging, and fouling of boilers in direct combustion systems (Lewandowski and Kicherer, 1997). It also reduces nutrient removal in the harvested biomass, increasing nutrient use efficiency. However, switchgrass yields also decrease following winters with above average snowfall, primarily due to an increase in the amount of biomass left behind by the baler (Adler et al., 2006). In this study, the un-harvested residual biomass averaged 44% of total biomass for the three years that harvests were taken. This was similar to the yield reduction observed by Adler et al. (2006).

Total residual biomass summed over the 2006, 2007, and 2008 harvests was $982 \text{ g CO}_2\text{-e m}^{-2}$, whereas, total NBP summed over the same period was $-467 \text{ g CO}_2\text{-e m}^{-2}$ (Table 2). It is possible that the ability to sequester C was directly related to the spring harvest schedule and the large amount of residual biomass under this system compared with fall harvests. In a 12-year study of four annual cropping systems in the Great Plains, Sherrod et al. (2003) found that soil organic carbon was directly related to the annualized stover production. Corn stover is increasingly being considered as a feedstock for cellulosic ethanol production. If stover is removed for ethanol production, Fronning et al. (2008) recommend that growers wishing to maintain or increase soil C will need to use C amendments such as manure, compost, or cover crops to replace the C removed in the stover. Our research reaffirms the trade-off that exists between biomass removal for energy production and inputs into the soil for C sequestration. The switchgrass in this study appeared to sequester C primarily because a substantial amount of aboveground biomass was left un-harvested.

Annual Re and GPP in the current study appeared to be lower than for similar warm-season grass ecosystems. Mean Re in the current study was 2854 and $\text{GPP} = 3391 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ (Table 2). In comparison, Re rates reported in the literature range from $3740 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ for a switchgrass riparian buffer in central Iowa (Tufekcioglu et al., 2001), to $4940 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ for a mixed tall-grass prairie including switchgrass in Kansas (Bremer et al.,

Table 3
Solar radiation and temperature for selected locations along a transect from 77.9 to 98.9° W. Data are for the growing season (May 1 to September 30) averaged over 26 years (1980–2005). Growing degree days (GDD) are calculated as $(T_{\max} + T_{\min})/2$ with a base temperature of 10 °C. Locations include Russell, KS, Columbia, MO, Springfield, IL, Indianapolis, IN, Akron, OH, and State College, PA.

Location	Latitude/longitude	Solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$)	Maximum T_{air} (°C)	Cumulative GDD (°C)
Kansas	38.9°N/98.9°W	21.5	28.8	1928
Missouri	38.8°N/92.2°W	20.9	27.6	1836
Illinois	39.8°N/89.7°W	20.5	27.2	1760
Indiana	39.6°N/85.9°W	21.4	26.6	1591
Ohio	40.9°N/81.4°W	18.8	24.7	1423
Pennsylvania	40.8°N/77.9°W	18.9	24.4	1301

1998). Suyker and Verma (2001) estimated annual daytime uptake of -2948 and nighttime respiration of $1966 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ for a native tall-grass prairie in Oklahoma. If daytime respiration can be assumed to roughly equal nighttime respiration, then GPP and Re from their study would be -4914 and $3932 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$, respectively, or about 45 and 38% greater than in the current study.

The lower Re in this study could be related to the lower soil temperatures observed in this study compared with studies from the Great Plains. In Bremer et al. (1998), maximum soil temperatures were as high as 33 °C, while maximum soil temperature was 29 °C for both years of the Suyker and Verma (2001) study. By comparison, maximum soil temperature was 28 °C during the first year of the current study then decreased to 22 °C the final two years (Table 1). Average annual Q_{10} for Re in the current study was 2.8 ± 0.2 . This was similar to the Q_{10} of 2.7 for switchgrass grown in eastern South Dakota (Lee et al., 2007a) and for semiarid grasslands in central North Dakota (Frank et al., 2002). The similarities in Q_{10} suggest that Re response to temperature for switchgrass plots in southwestern Pennsylvania was similar to the temperature response in the northern Great Plains, and confirms the suggestion that lower Re at the current research site resulted from lower soil temperature.

Mean annual soil temperature decreased from 11.4 in 2004–2005 to 10.1 °C in 2007–2008. This caused the difference between soil and air temperature to decrease each year, from 1.4 °C in 2004–2005 to 0.3 °C in 2007–2008. Reduced soil heating probably resulted from the increasingly greater aboveground biomass each year which would have reduced light penetration to the soil surface. Bremer et al. (1998) found that shading in non-clipped plots caused them to be about 3 °C cooler than clipped plots during the summer, with the lower temperatures persisting into late-autumn. They suggested that the lower temperature would have reduced Re by $0.11 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($9.5 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) during the warmest summer days. The presence in the field of the previous year's growth until late-April or early-May, combined with large amounts of residual biomass following harvests, probably slowed springtime soil warming in our study, contributing to lower annual soil temperature as the study progressed.

Although annual GPP was lower than estimates from Suyker and Verma (2001), maximum mid-day GPP of around $-1.9 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ was greater than the -1.4 to $-1.5 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ observed for mixed tallgrass prairie (Verma et al., 1992), and the maximum daily NEE of about $-30 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ (Fig. 3) was similar to values for native prairie (Dugas et al., 1999). Even though relatively high maximum uptake rates were observed, it is possible that GPP in this system was limited by both temperature and light. Warner et al. (1987) found that switchgrass photosynthesis was maximized between about 30 and 35 °C and similar results were observed by Polley et al. (1992). In this study, maximum air temperature each year ranged from 31 to 33 °C. More commonly, mid-day air temperature in July and August ranged between 25 and 30 °C, with temperatures more likely to be below 25 than above 30 °C. This suggests that for most of the time air temperature was sub-optimal for photosynthetic CO_2 uptake. In addition to temperature

limitations, Verma et al. (1992) found that photosynthetic light saturation did not occur in warm-season prairie at PAR levels as high as $2100 \mu\text{mol m}^{-2} \text{ s}^{-1}$. At this location, mid-day PAR was never as high as $2100 \mu\text{mol m}^{-2} \text{ s}^{-1}$, and more commonly ranged from 1400 to $1700 \mu\text{mol m}^{-2} \text{ s}^{-1}$. Canopy photosynthesis also did not saturate at PAR levels common to southwestern Pennsylvania and would likely have been greater if solar radiation had been similar to levels observed in the Great Plains.

To further explore the potential effects of temperature and light on differences between GPP in Pennsylvania compared with the Great Plains and Midwest, growing season climate data were collected for sites along a transect at approximately 40° N latitude from central Kansas to central Pennsylvania (Table 3). Moving from west to east there was a sharp decrease in solar radiation between central Indiana and eastern Ohio. Solar radiation in central Pennsylvania was about 10% lower than the average from Indiana to Kansas. Similarly, both average maximum daily air temperature and cumulative growing degree days (GDD) increased from east to west. Relatively low solar radiation was observed for several locations throughout Pennsylvania and New York (data not shown), suggesting that light availability could be limiting GPP throughout the state and throughout much of the northeastern US.

The lower annual GPP in this study also resulted from a shorter growing season compared to the Great Plains. Substantial CO_2 uptake in the spring did not begin until 2–3-wk after mean daily air temperature increased above 10 °C, and usually occurred around the second week in May (about DOY 126–133). By the last week of May (about DOY 147) the field had switched from a net CO_2 source (positive NEE) to net sink (negative NEE) as GPP exceeded Re. The field typically remained a sink until the beginning of September (about DOY 245) with GPP becoming zero by early October (about DOY 280). Thus CO_2 uptake occurred for about 147 to 154 d and the field was a net sink for 98 d. No comparable GPP data are available for other warm-season ecosystems. However, native prairies have been shown to be net sinks for 125 d (Dugas et al., 1999), about 150 d (Suyker and Verma, 2001), or 119–179 d depending on year and grazing treatment (Owensby et al., 2006). These results represent a 21–83% increase in the length of the CO_2 accumulation period in the Great Plains compared to our site in southwestern Pennsylvania.

Differences in NEE among years were related to changes in Re rather than to differences in GPP (Table 2), which varied little from year to year. Skinner (2008) obtained a similar result when comparing two cool-season pastures in central Pennsylvania, noting that daytime NEE was identical between pastures whereas nighttime respiration was reduced in the pasture with the greatest annual NEE. Valentini et al. (2000) also concluded that difference in forest NEE along a north–south transect in Europe resulted from differences in Re and not in GPP.

Even though GPP did not change from year to year, aboveground biomass increased each year of the study. Switchgrass has a reputation of being slow to establish (Parrish and Fike, 2005), and it is thought that high C partitioning to roots during establishment may be at least partially responsible for slow aboveground development. Only about 10% of the CO_2 fixed during the 2005 growing season

was found in aboveground biomass (harvested plus residual) the following spring. This percentage increased to 36% by spring 2008. Root biomass in June 2006 was $529 \pm 58 \text{ g m}^{-2}$ compared with $304 \pm 41 \text{ g m}^{-2}$ in June 2007, suggesting that root growth was initially high then decreased over time. Frank et al. (2004) found that drought stress greatly increased root biomass compared to non-stress years. In the current study, drought stress during the summer of 2005 could also have limited aboveground biomass production and increased belowground partitioning.

Seasonal CO_2 flux dynamics were significantly different in 2004–2005, with greater GPP (Fig. 2), NEE (Fig. 3), and ET (Fig. 4) in April 2005 compared with later years. The difference was probably due to the presence in 2005 of cool-season annual weeds which began CO_2 uptake and growth earlier in the year than switchgrass. These weeds were essentially absent in later years because of their inability to compete with the mature switchgrass. Thus, water and vapor fluxes the last three years represented a relatively pure switchgrass stand, whereas, the first year represented more of a cool-season/warm-season mixture.

As with GPP and Re, daily and annual ET was also lower than reported rates for native prairie. Verma et al. (1992) observed peak growing season ET on the Konza prairie in Kansas of between 3.9 and 6.6 mm d^{-1} under adequate soil moisture conditions. During a dry period in late-July and early-August, ET decreased to 2.9 – 3.8 mm d^{-1} . Later Hutchinson et al. (2008) ensured adequate moisture by irrigating the same prairie. They also found that growing season ET under well-watered conditions ranged from 4 to 7 mm d^{-1} . In the current study, the maximum observed ET was 3.7 mm d^{-1} in June 2007 (Fig. 4). Greatest ET occurred during June and July each year, and averaged 2.8 mm d^{-1} , with an average annual maximum of 3.3 mm d^{-1} . In general, transpiration depends on stomatal conductance, net radiation, air saturation deficit, temperature, and wind speed (Jarvis and McNaughton, 1986). This southwestern Pennsylvania site had lower maximum and mean annual temperature than the Konza prairie (Hutchinson et al. 2008). In addition, daytime wind velocity was low (mean for the four years = 1.8 m s^{-1}) and relative humidity in the region tends to be high. Low temperature, low wind velocity, and high humidity would all result in relatively low ET.

Evapotranspiration in this study also appeared to be lower than reported values for other crops. Reported mid-summer ET rates include 5 – 10 mm d^{-1} for alfalfa (*Medicago sativa*) growing in Minnesota (Carter and Sheaffer, 1983), 4 – 6 mm d^{-1} for soybean (*Glycine max*) in Nebraska (Clawson et al., 1986), and 3 – 6 mm d^{-1} for Kentucky bluegrass (*Poa pratensis*) in New York (Ebdon et al., 1999). Suyker and Verma (2009) reported average annual ET of 688 mm for irrigated maize (*Zea mays*), 631 mm for rainfed maize, 602 mm for irrigated soybean, and 576 mm for rainfed soybean grown in Nebraska. Even though annual ET in the last mentioned study was 22 – 45% greater than in the current study, dormant season ET (November to April) was nearly identical, averaging 105 mm in this study compared with 115 mm in Suyker and Verma (2009).

The period of maximum WUE changed slightly from year to year, but was generally greatest during June and July (Fig. 5). The main exception was 2005 when peak WUE was delayed about one month and did not occur until the beginning of July. Stout (1992) found that switchgrass WUE efficiency was considerably higher than for the cool-season perennial, orchardgrass (*Dactylis glomerata*). Warm-season grasses in the Great Plains also generally have greater WUE than associated cool-season species (Eggemeier et al., 2006). It is possible that the relatively low WUE during June 2005 resulted from the abundant presence of cool-season annual grasses. Peak WUE ranged from 12 to $13 \text{ mg CO}_2 \text{ g H}_2\text{O}$, with maximum values for any given year ranging from 12 to $15 \text{ mg CO}_2 \text{ g H}_2\text{O}$. This was similar to the maximum WUE of about $12 \text{ mg CO}_2 \text{ g H}_2\text{O}$ observed by Eggemeier et al. (2006) in the Sandhill grassland of Nebraska.

5. Conclusions

Averaged over the first four years of production, this switchgrass field was a net sink of $-142 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ ($-39 \text{ g C m}^{-2} \text{ yr}^{-1}$), suggesting that in addition to their primary function as a source of renewable energy, switchgrass bioenergy crops in the northeastern USA can immediately begin to sequester CO_2 during the first few years following establishment. The size of the sink each year was a function of changes in Re rather than GPP which remained remarkably constant across years. The lack of a relationship between GPP and aboveground biomass production suggests that partitioning of photoassimilate to roots was initially high then decreased over time. Water use by the system appeared to be relatively low compared to other crops and regions, and water use efficiency was high. Annual precipitation was more than two times greater than annual ET and brief periods of drought stress did not appear to adversely affect GPP. Future research to determine the relative contributions of shoots, roots, and soil organisms to total ecosystem respiration is necessary to fully understand the processes controlling soil carbon sequestration.

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